# Explicit Modeling of the Inner-Core Cloud and Flow Structures of Hurricanes

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## LONG-TERM GOALS

Improve the prediction of hurricane track, intensity and intensity change 3-5 days in advance; and provide a better understanding of the fundamental processes taking place in tropical cyclones from its genesis to hurricane and landfalling stages, including the inner-core clouds/precipitation and catastrophic winds.

## OBJECTIVES

(i) Develop a three-dimensional hurricane-vortex initialization scheme using the Advanced Microwave Sounding Unit (AMSU) data, radar, QuickSCAT, and other *in situ* and remote sensing observations; (ii) improve the formulations of cloud microphysics, boundary-layer physics and air-sea interactive processes in hurricane models; (iii) study the larger-scale environments that are favorable for, and the processes leading to tropical cyclogenesis; and (iv) examine the roles of vortex-Rossby waves and gravity waves in the hurricane intensity change and in the formation of spiral rainbands.

## APPROACH

The non-hydrostatic version of the Penn State/NCAR mesoscale model (i.e., MM5) was used as a research tool. Satellite and field observations were used to represent the initial conditions for hurricane vortices and validate the model simulations. The four-dimensional (4D), dynamically consistent, high-resolution model data were used to examine the hypotheses and theories related to hurricane inner-core dynamics. Dr. F. Weng and my former Ph.D. student, Dr. T. Zhu of NOAA/NESDIS, and Prof. M.K. Yau and Dr. X. Wang of McGill University played important roles in this project.

## WORK COMPLETED

(i) An initialization scheme for hurricane vortices has been developed through the three-dimensional (3D) retrieval of the Advanced Microwave Sounding Unit (AMSU) measurements in combination with surface observations; (ii) A five-day explicit simulation of Hurricane Bonnie (1998) has sucessfully been performed with the finest grid size of 4 km to examine the impact of the AMSU data and the predictability of various inner-core structures; (iii) A series of 72-h simulations of Hurricane Andrew (1992) has been conducted to study the impact of varying vertical resolutions and time-step sizes on hurricane intensity and inner-core structures; and (iv) A piecewise potential vorticity (PV) inversion technique has been developed to examine the balanced versus unbalanced characteristics of hurricanes.

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14. ABSTRACT

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## RESULTS

*(a) Impact of initializing Hurricane Bonnie (1998) with the AMSU data* (see Zhu et al. 2002)

Due to the lack of meteorological observations over the tropical oceans, almost all the current hurricane models require bogusing of a vortex into the large-scale analysis of the model initial state. Thus, we have developed an algorithm to construct hurricane vortices using the Advanced Microwave Sounding Unit (AMSU-A) data. Under the rain-free atmospheric conditions, the temperature profile could be retrieved with a root mean square error of 1.5 $^0$C. Under the heavy rainfall conditions, measurements from channels 3 - 5 are removed in retrieving temperatures. An application of this algorithm to Hurricane Bonnie (1998) shows well the warm-core eye and strong thermal gradients across the eyewall. The rotational and divergent winds are obtained by solving the nonlinear balance and Omega equations using the large-scale analysis as the lateral boundary conditions; see Fig. 1 for the retrieved winds. In doing so, the sea-level pressure distribution is empirically specified, and the geopotential heights are calculated from the retrieved temperatures using hydrostatic equation. The so-derived temperature and wind fields associated with Bonnie compare favorably to the dropsonde observations taken in the vicinity of the storm. The initial moisture field is specified based on the AMSU-derived total precipitable water.

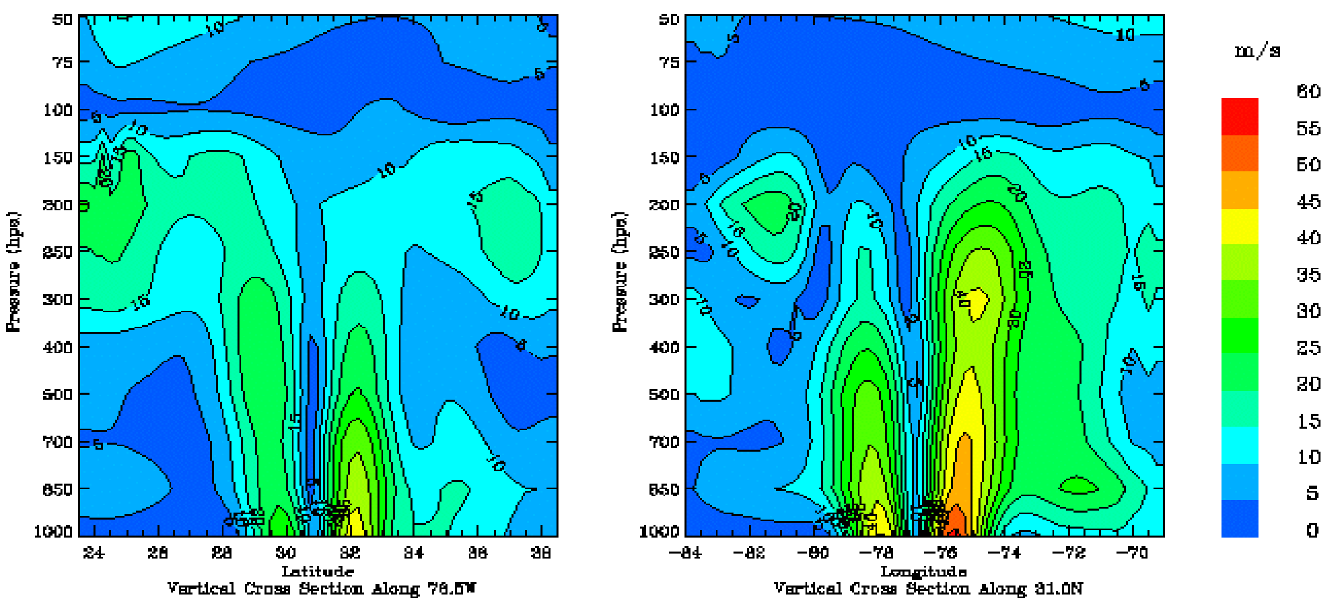


***Figure 1. Vertical (a) south-north, and (b) west-east cross sections of the tangential winds for Hurricane Bonnie (1998), at intervals of 5 m s$^{-1}$, retrieved from the AMSU-derived temperatures at 0000 UTC 26 August 1998.***

The effectiveness of using the retrieved hurricane vortex as the model initial conditions is tested using three 48-h simulations of Bonnie with the finest grid size of 4 km, triply nested version of the MM5. It is found that the control run captures reasonably well the track and rapid deepening stage of the storm. The simulated radar reflectivity exhibits highly asymmetric structures of the eyewall and cloud bands, similar to the observed. A sensitivity simulation is conducted, in which an axisymmetric vortex is used in the model initial conditions. The simulated features are less favorable compared to the

observations. Without the incorporation of the AMSU data, the simulated intensity and cloud structures differ markedly from the observed.

*(b) A five-day explicit simulation of Hurricane Bonnie (1998)* (see Zhu et al. 2003)

We have conducted a 5-day explicit simulation of Hurricane Bonnie (1998) using the MM5 with the finest grid length of 4 km. The model reproduces reasonably well the hurricane intensity and intensity changes, asymmetries in cloud and precipitation as well as the vertical structures of dynamic and thermodynamic fields in the eye and eyewall. Of interest is that the storm deepens markedly in the first 2 days during which period its environmental vertical shear increases substantially. It is found that this deepening could occur because of the dominant energy supply by a strong low-level southeasterly flow into the eastern eyewall plus the presence of underlying warm SST and favorable upper-level divergent outflow. However, the approaching of a strong upper-level northwesterly flow tends to generate mass convergence, and subsidence warming and drying, thereby suppressing the development of deep convection in the western semicircle. This gives rise to wavenumber-1 asymmetries in clouds and precipitation (i.e., a partial eyewall), and the eastward tilt of the eyewall and storm center. Both the observed and simulated storms also exhibit eyewall replacement scenarios in which the storms weaken as double eyewalls appear and then re-intensify as their inner eyewalls diminish and concentric eyewalls develop (see Fig. 2).

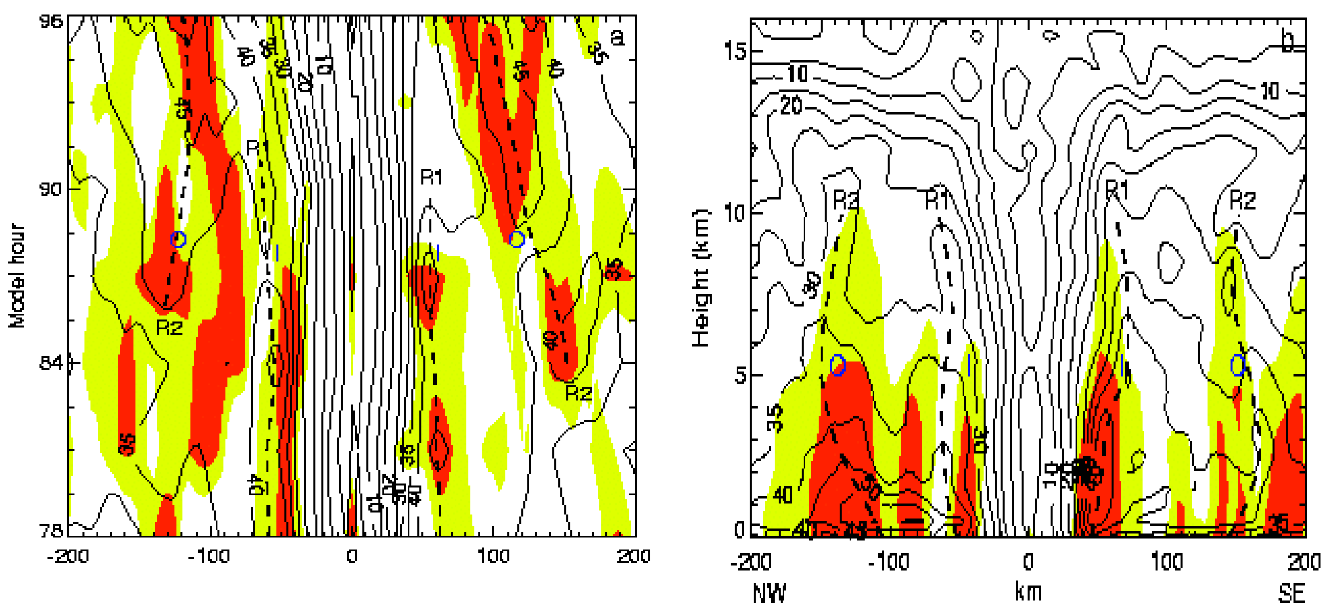


***Figure 2. (a) Time and northwest-southeast cross section at z = 3 km; and (b) Vertical cross section of the horizontal wind speeds, both at intervals of 5 m s$^{-1}$, from the 87-h simulation of Hurricane Bonnie. Shadings denote the simulated radar reflectivity at 30 and 40 dBZ and thick-dashed lines denote the axes of the radius of maximum winds. Letters, 'O' and 'I', denote the outer and inner eyewalls, respectively.***

*(c) Impact of vertical resolution on hurricane intensity and structures* (see Zhang & Wang 2003)

In view of the growing interests in the explicit modeling of clouds and precipitation of tropical cyclones, the effects of varying vertical resolution and time-step sizes on the 72-h explicit simulation

of Hurricane Andrew (1992) are studied using the MM5 with the finest grid size of 6 km. It is shown that changing the vertical resolution and time-step size has significant effects on hurricane intensity and inner-core cloud/precipitation, but little impact on the hurricane track. In general, increasing vertical resolution tends to produce a deeper storm with lower central pressure and stronger three-dimensional winds, and more precipitation [e.g., from the low-resolution 23 layers (LRL23) to the control 46 layers (CTL46) and high-resolution 69 layers (HRL69), see Fig. 3]. Similar effects, but to a less extent, occur when the time-step size is reduced. It is found that increasing the low-level vertical resolution (i.e., HLT35 and HBL32) is more efficient in intensifying a hurricane, whereas changing the upper-level vertical resolution (i.e., HUT35) has little impact on the hurricane intensity (Fig. 3). Moreover, the use of a thicker surface layer tends to produce higher maximum surface winds. It is concluded that the use of higher vertical resolution, a thin surface layer and smaller time-step sizes, along with higher horizontal resolution, is desirable to model more realistically the intensity and inner-core structures and evolution of tropical storms as well as the other convectively driven weather systems.

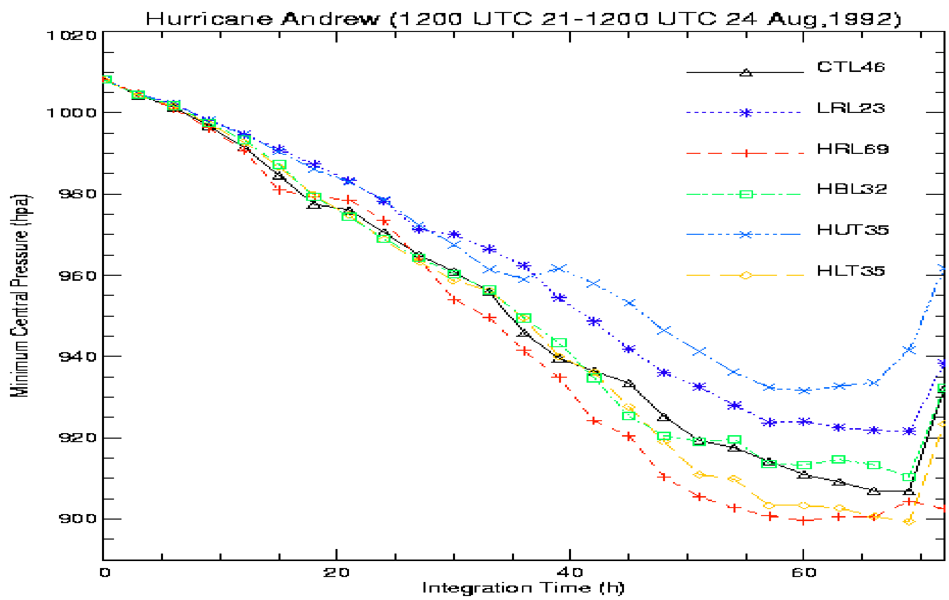


***Figure 3. Time series (72-h) of the minimum central pressure from all sensitivity experiments using various vertical layers from 23 to 46 and 69. HUT35, HLT35 and HBL32 denote 35 layers with high resolution in the upper and low troposphere, and 32 layers in the boundary layer, respectively.***

*(d) Retrieving the 3D quasi-balanced hurricane flow through PV inversion* (see Wang & Zhang 2003)

Because of the lack of 3D high-resolution data and the existence of highly non-elliptic flows, few studies have been conducted to investigate the inner-core quasi-balanced characteristics of hurricanes. We have recently developed a potential vorticity (PV) inversion scheme that includes the non-conservative processes of friction, diabatic heating and water loading. It requires hurricane flows to be statically and inertially stable but allows for the presence of small negative PV. To facilitate the PV inversion with the nonlinear balance (NLB) equation, hurricane flows are decomposed into an axisymmetric, gradient balanced reference state (e.g., $\overline{\psi}$ and $\overline{\phi}$ ) and asymmetric perturbations (e.g., $\psi'$ and $\phi'$). Meanwhile, the non-ellipticity of the NLB equation is circumvented by multiplying a small

parameter, ε, and combining it with the PV equation [see Eq. (1)], which effectively reduces the influence of anticyclonic vorticity. A quasi-balanced ω equation in pseudo-height coordinates is derived, which includes the effects of friction and diabatic heating as well as differential vorticity advection and the Laplacians of thermal advection by both nondivergent and divergent winds.

$$
\begin{aligned}
(\varepsilon f + \frac{\partial^2\bar{\phi}}{\partial z^2})\nabla_h^2\psi' = {} & q' - (f + \nabla_h^2\bar{\psi})\frac{\partial^2\phi'}{\partial z^2} + \frac{\partial^2\bar{\psi}}{\partial x\partial z}\frac{\partial^2\phi'}{\partial x\partial z} + \frac{\partial^2\psi'}{\partial x\partial z}\frac{\partial^2\bar{\phi}}{\partial x\partial z} + \frac{\partial^2\bar{\psi}}{\partial y\partial z}\frac{\partial^2\phi'}{\partial y\partial z} + \\
& \frac{\partial^2\psi'}{\partial y\partial z}\frac{\partial^2\bar{\phi}}{\partial y\partial z} - \nabla_h^2\psi'\frac{\partial^2\phi'}{\partial z^2} + \frac{\partial^2\psi'}{\partial x\partial z}\frac{\partial^2\phi'}{\partial x\partial z} + \frac{\partial^2\psi'}{\partial y\partial z}\frac{\partial^2\phi'}{\partial y\partial z} + \varepsilon[\nabla_h^2\phi' - \beta\frac{\partial\psi'}{\partial y}{}' - 2(\frac{\partial^2\bar{\psi}}{\partial x^2}\frac{\partial^2\psi'}{\partial y^2} \\
& - 2\frac{\partial^2\bar{\psi}}{\partial x\partial y}\frac{\partial^2\psi'}{\partial x\partial y} + \frac{\partial^2\psi'}{\partial x^2}\frac{\partial^2\bar{\psi}}{\partial y^2}) - 2(\frac{\partial^2\psi'}{\partial x^2}\frac{\partial^2\psi'}{\partial y^2} - \frac{\partial^2\psi'}{\partial x\partial y}\frac{\partial^2\psi'}{\partial x\partial y}) - \frac{\partial f_x}{\partial x} - \frac{\partial f_y}{\partial y}]
\end{aligned}
\qquad (1)
$$

The quasi-balanced PV-ω inversion system is tested with an explicit simulation of Hurricane Andrew (1992) with the finest grid size of 6 km. It is shown that (i) the PV-ω inversion system could recover almost all typical features in a hurricane; and (ii) a sizeable portion of the 3D hurricane flows are quasi-balanced, such as the intense rotational winds, organized eyewall updrafts and subsidence in the eye, cyclonic inflow in the boundary layer and upper-level anticyclonic outflow. It is found, however, that the boundary-layer cyclonic inflow and upper-level anticyclonic outflow also contain significant unbalanced components. In particular, a low-level outflow jet near the top of the boundary layer is found to be highly unbalanced (and supergradient). These findings are supported by both locally calculated momentum budgets and globally inverted winds.

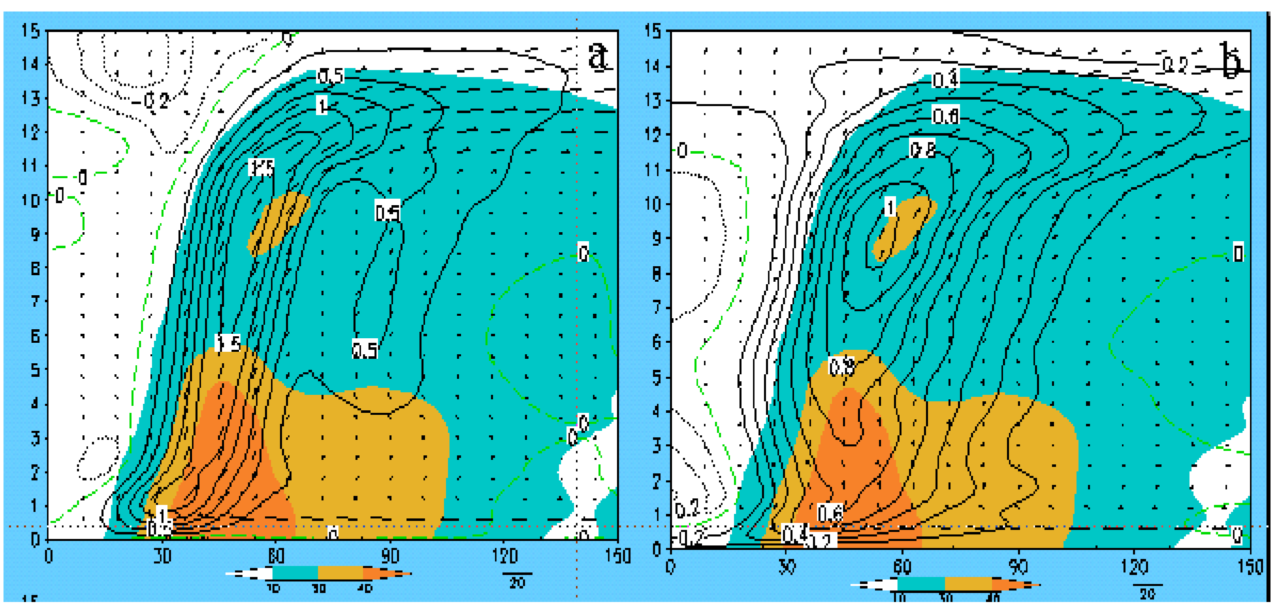


***Figure 4. Height-radius cross sections of vertical motion within the radius of 150 km from (a) the model output; and (b) the PV-ω inverted from the 57-h simulation valid at 2100 UTC 23 August 1992. Shadings denote the simulated radar reflectivity greater than 15 and 35 dBz, which represents roughly the distribution of precipitation with two different intensities. Solid (dashed) lines are for positive (negative) values.***

## IMPACT/APPLICATIONS

The AMSU-retrieval algorithm could (i) provide an objective, observation-based way to incorporate a dynamically consistent vortex with reasonable asymmetries into the model initial conditions, and (ii) estimate three-dimensional hurricane flows. Our research results suggest that (i) in order to predict the hurricane intensity and inner-core structures, all hurricane models should use high vertical resolution as the horizontal resolution increases; (ii) the eyewall replacement process and other inner-core features could be predicted up to 3-5 days, which would aid in predicting the hurricane intensity changes; and (iii) the piecewise PV-ω inversion system could be used to separate the unbalanced from quasi-balanced flows for studies of balanced dynamics and propagating inertial-gravity waves in hurricanes.

## TRANSITIONS

Our algorithm for retrieving the temperature and wind fields from the AMSU data will be operationally posted soon on the website of NOAA/NESDIS by Dr. F. Weng's group. This will allow hurricane forecasters to estimate the intensity of hurricane flows and hurricane modelers to initialize their numerical models.

## RELATED PROJECTS

This project is closely related to the projects funded by NOAA/NESDIS on the retrieval of temperature and winds from the AMSU measurements, NSF on the high-resolution simulation of Hurricane Andrew (1992), and NASA on the simulation of Hurricane Bonnie (1998).

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